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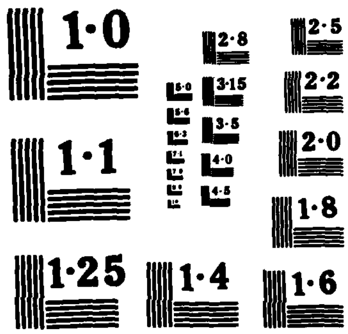

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DREDGING OPERATIONS TECHNICAL SUPPORT PROGRAM

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COMPARISON OF THE HEAVY-METAL UPTAKE OF *CYPERUS ESCULENTUS* AND OF AGRONOMIC PLANTS GROWN ON CONTAMINATED DUTCH SEDIMENTS

by

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Heavy-metal uptake by *Cyperus esculentus* from three highly contaminated fluvial sediments and from two uncontaminated substrates under reduced (flooded) and oxidized (upland) disposal conditions was studied in the greenhouse. Heavy-metal uptake by lettuce, radish, spring wheat, and red fescue grass from four highly contaminated sediments and one uncontaminated fluvial sediment under oxidized soil conditions was also studied.

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The sediments were collected from upland disposal sites or from polders where the clay soils originate from sedimentation under natural conditions in the freshwater tidal area. Part of the substrates was used under anaerobic conditions by immersing the soil in the inner container of a double bucket filled with demineralized water and maintaining a 5-cm layer over the soil. *Cyperus esculentus* from tubers planted in the sediments was grown to maximum vegetative growth (45 days). Seeds of lettuce, radish, spring wheat, and red fescue grass were planted in the relevant substrates. The crops were harvested at commercial maturity; red fescue grass was cut four times at 15-cm length. All plant species performed well, both on uncontaminated and contaminated substrates.

Under upland conditions, *Cyperus esculentus* accumulated more Cd, Cu, Ni, and Zn, and less Pb than under flooded conditions. On contaminated substrates, *Cyperus* contained more Cd and Zn than on the reference fluvial clay soil, both under upland and flooded conditions. In nearly all crops cultivated on contaminated substrates, Cd, Ni, Pb, and Zn accumulated. Only in red fescue was accumulation limited to Pb and Zn; there was no response to the increased concentrations of the other metals in the substrate.

Good correlations between substrate (total) and plant (foliar) metal concentrations were found to exist for Cd and Zn in all crops except grass, and in lettuce and spring wheat for Ni. Both DTPA-extractable and total metal in the substrates were related to plant metal concentrations, but for Zn the best fit was obtained for the DTPA-extractable fraction.

The Cd concentrations in consumable products and feeds grown on contaminated river sediments exceeded the tentative maximum values for consumable products; Cu and Pb remained well under the limits for feeds in all products. The concentrations of the other metals examined were considered to be harmless.

PREFACE

This study was conducted at the Institute for Soil Fertility, Haren, The Netherlands, from March 1981 through January 1982 by Dr. W. van Driel, Department of Soil Chemistry, and Dr. Ir. K.W. Smilde and Ing. B. van Luit, Department of Fertilization of Field Crops and Grassland.

The study is one of a series of pot experiments conducted at the Institute for Soil Fertility on growth and heavy-metal uptake by commercial crops, cultivated on contaminated river sediments and dredged material. The connection with growth and heavy-metal uptake of marsh plants was made in discussions in the Plant Bioassay Working Group of the US Army Engineer Waterways Experiment Station (WES), Vicksburg Miss., with, among others, Drs. C.R. Lee, B.L. Folsom, Jr., and J.W. Simmers of WES. Practical information, materials, and *Cyperus* plants necessary to conduct the pot experiment were provided by these staff members of WES. The project was initially funded through the Dredging Operations Technical Support (DOTS) Program and subsequently by the Long-Term Effects of Dredging Operations (LEDO) Program. Both DOTS and LEDO are within the Environmental Effects of Dredging Programs, Dr. R.M. Engler, Manager. The project was coordinated by the United States Army Research Development and Standardization Group (London, U.K.), Mr. W.E. Grabau, Chief Environmental Sciences Branch.

This study was under the general supervision of Dr. R.M. Engler, Chief, Contaminant Mobility and Regulatory Criteria Group, Mr. D.L. Robey, Chief, Ecosystem Research and Simulation Division, and Dr. J. Harrison, Chief, Environmental Laboratory, WES.

A quantity of highly contaminated dredged material from the Neckar River in the Federal Republic of Germany was supplied by the 'Institut fur Sedimentforschung' of the University of Heidelberg. The assistance of Mr. W. Schuurmans is acknowledged, who performed all the analytical work and most of the statistical work.

During the preparation of this report, COL Tilford C. Creel, CE, and COL Robert C. Lee, CE, were Commanders and Directors of WES and Mr. F.R. Brown was Technical Director. At the time of publication, COL Allen F. Grum, CE, was Director and Dr. Robert W. Whalin was Technical Director.

This report should be cited as follows:

van Driel, W., Smilde, K.W., and van Luit, B. 1985. "Comparison of the Heavy-Metal Uptake of *Cyperus Esculentus* and of Agronomic Plants Grown on Contaminated Dutch Sediments," Miscellaneous Paper D-83-1, prepared by Institute for Soil Fertility, Haren, The Netherlands, for the US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

CONTENTS

COMPARISON OF THE HEAVY-METAL UPTAKE OF *CYPERUS ESCULENTUS* AND OF AGRONOMIC PLANTS GROWN ON CONTAMINATED DUTCH SEDIMENTS

1. INTRODUCTION

Enormous quantities of sediments have to be removed from waterways and harbour basins to keep them open to navigation. The sediments are often polluted with heavy metals, pesticides, oil residues, and other persistent organic waste products, rendering them unfit for an appropriate agronomic use. One disposal alternative is creation of artificial marshlands. In the United States of America many such marshes can be found, both in fresh, brackish, or saltwater environments, submerged (flooded) or upland.
Such a use of contaminated sediments may have adverse consequences to the health and development of wildlife and its possible consumers. The U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., is developing a bioassay for testing the environmental quality of a dredged material. In this study the procedure for a plant bioassay under fresh-water conditions has been used under Dutch conditions with contaminated sediments from Dutch waterways, with the North-American fresh-water marsh plant *Cyperus esculentus* as the test plant. These sediments were also used in pot experiments with agronomic crops, so that the results of the bioassay could be related to crop performance on contaminated fluvial soils.

1.1. Scope of work

A study of plant uptake of Cu, Zn, Cr, Ni, Pb, and Cd by the fresh-water marsh plant *Cyperus esculentus* was conducted with sediments under extreme conditions of oxidation and reduction, viz., under flooded and upland conditions.

In a second study the same sediments were planted to spring wheat, butterhead lettuce, radish, and red fescue grass. The sediments selected ranged from uncontaminated (control) to highly contaminated with heavy metals. The plants were grown to maturity (spring wheat, radish, lettuce),

or maximum vegetative growth *(Cyperus)*, or cut four times at an average leaf length of 15 cm (red fescue). At harvest, dry-matter yields of the plants and metals in tubers (radish), leaves *(Cyperus*, radish, lettuce, grass), seeds (spring wheat), and straw (spring wheat) were determined.

Sediments were analysed for total- and DTPA-extractable heavy metals.

The specific objectives of the study were:

1. To evaluate the suitability of the plant bioassay as a measure of the hazardous nature of a contaminated sediment.
2. To compare heavy-metal uptake of *Cyperus esculentus* with that of selected agronomic plant species, thereby utilizing an appropriate number of contaminated and reference sediments.

1.2. Experimental design

The experiment comprised:

* One uncontaminated fluvial clay soil,
* four contaminated fluvial clay soils,
* one reference soil (sandy loam), supplied by the Waterways Experiment Station.
* Three contaminated sediments, one uncontaminated sediment, and the WES reference soil were planted to the freshwater marsh plant yellow nut sedge, *Cyperus esculentus.*
* *Cyperus esculentus* was cultivated under upland (oxidized) and flooded (reduced) conditions.
* Spring wheat, radish, lettuce, and red fescue were sown in four contaminated and one uncontaminated sediments under upland (oxidized) conditions.
* Each plant/sediment combination was replicated four times, except radish and lettuce, which were replicated eight times.
* There were 120 pots, 100 under upland conditions and 20 under flooded conditions

1.3. Sediment selection

The aim of the bioassay experiment was to test dredged material. In The Netherlands the greatest dredging operations are done in the waterways

and basins of the harbours of Rotterdam. The dredged material consists of a mixture of river sediments from the rivers Rhine and Meuse, and marine sediments from the North Sea. The river sediments are heavily polluted with heavy metals and organic compounds; the marine sediments are much less polluted. For this series of experiments, river sediments and dredged material were selected with a wide range of heavy metal contamination. and with about 50% particles <16 μm. The sediments are described below:

* *Control soil Noordbovenpolder* (Code: NP). River clay sedimented in situ in the freshwater tidal area of the rivers Rhine and Meuse (Dordtse Biesbosch). The Noordbovenpolder from which the sediment was obtained was diked in 1780 and has been in permanent grassland for at least 30 years.
* *Spieringpolder* (Code: SP). Young river clay sedimented in situ in the freshwater tidal area of the rivers Rhine and Meuse. The polder from which the sediments were obtained was diked in 1953 and is moderately contaminated with heavy metals. Since its reclamation the land has been used for growing arable crops.
* *Oostabtspolder* (Code: OP). Disposal site for dredged material from the Rotterdam harbour near Rotterdam. The sediment was obtained from section 5, which has been fallow since the last disposal of dredged material in 1974.
* *Broekpolder* (Code: BP). Disposal site for dredged material from the Rotterdam harbours near Vlaardingen. The sediment was obtained from section 9, which has been fallow since the last disposal of dredged material in 1975.
* *Neckar sludge* (Code: NS). Disposal site for dredged material from the river Neckar in the Federal Republic of Germany, a tributary to the river Rhine. The sediment was dredged near Lauffen and disposed on land in 1979.

* *WES reference soil* (Code: WS). To compare growth and appearance of *Cyperus esculentus* under flooded and upland conditions with the results obtained at the Waterways Experiment Station, a reference soil was supplied and included in the experiments. This poor, sandy loam from Vicksburg, differed in many respects from the fertile river sediments selected for the experiments. The results of *Cyperus* grown on the WES soil will be used only as a reference for local growing conditions.

2. EXPERIMENTS WITH *CYPERUS ESCULENTUS*

2.1. Treatment of sediments

In these experiments the sediments were taken from upland fields or disposal sites that have not been flooded for many years. The sediments have "ripened" both physically and chemically and, consequently, a microbial population adapted to upland conditions will be present. After collection the soil was air dried and ground to pass a 2-mm screen. The soil was moistened to 70% of field capacity and used for the upland *Cyperus* and agronomic experiments.

Flooded conditions were obtained by immersing the soil in the inner container of a double bucket filled with demineralized water and maintaining a 5-cm layer of water over the soil.

In the experiments by Folsom *et al.* (1981) the sediments were collected in situ under flooded conditions. This anaerobic status was maintained throughout the experiments with *Cyperus* under flooded conditions. This warrants that no major changes will occur in the microbial population of the sediment. The upland conditions were obtained by air-drying the slurry and subsequently grinding the resulting sediment cake to pass a 2-mm screen. This upland soil cannot be considered to be "ripened".

These differences in pretreatment and origin of the sediments decrease the mutual comparability of the experimental results. The period of immersion required to obtain conditions for plant growth and uptake of heavy metals similar to those under continuous flooding is not known. A preliminary experiment is described in the next section.

2.2. Incubation experiment

This experiment studied the effect on growth and chemical composition of *Cyperus* plants of incubating the flooded soil for 3 or 5 weeks prior to planting. Two soils were included: an uncontaminated old river clay from the Noordbovenpolder (NP) and heavily contaminated dredged

material from the disposal site Broekpolder near Vlaardingen (BP). Both sites have been under aerobic field conditions for many years. After incubation, three *Cyperus esculentus* tubers, with a sprout length of about 7 cm, were planted in each 5-litre pot. For comparison, two upland pots were also included. The plants were grown in a growth cabinet under the following conditions: day period of 16 hours at 30 ^{o}C, relative humidity 73%; night period of 8 hours at 24 ^{o}C, relative humidity 76%; light intensity of 20,000 lux; and a growth period of 74 days.

The results can be summarized as follows:

Effect of incubation period of flooded soils on growth and chemical composition of *Cyperus esculentus*.

Soil code	Condition	Treatment	Yield g dry matter per pot	Composition Cu	Zn	Cd
					$mg.kg^{-1}$	
NP	upland	-	4.87	20.5	100	2.51
NP	flooded	3 weeks incub.	11.16	20.2	83	0.99
NP	flooded	5 weeks incub.	11.07	17.9	80	0.55
BP	upland	-	6.42	21.6	162	12.8
BP	flooded	3 weeks incub.	9.65	31.6	276	7.68
BP	flooded	5 weeks incub.	8.65	30.4	223	6.36

Growth of *Cyperus* was not affected by the shorter incubation period of the sediment. The concentrations of metals, especially cadmium and zinc, in the leaves tended to decrease in the longer incubation period. In the double-bucket experiment a period of incubation of about 8 weeks resulted in lower metal contents in the *Cyperus* leaves. Growing conditions in the greenhouse were entirely different from those in the growth cabinet.

2.3. *Experimental unit used for growing Cyperus esculentus*

A detailed description of the "double-bucket" container is given by Folsom *et al.* (1981). The double bucket consists of two polyethylene containers,

a small inner container (7.6 litres) in which the soil or sediment is placed, and a large outer container (22.7 litres) for control of watering, in which the small container is placed on two 2.54-cm PVC pipes. The inner container has 9 holes of 7-mm diameter in the bottom, covered with polyethylene sponge. The sponge is covered by a layer of washed sand, acts as a filter to allow water movement into and out of the sediment, and keeps the sediment from draining out of the bottom of the inner container.

In the *"upland" experiment* a tensiometer was placed in the sediment, with the porous element in the middle of the pot. Water was applied when the tensiometer reading exceeded 30% by filling the outer container with demineralized water up to the level of the sediment in the inner container. At a tensiometer reading of about zero, the water was siphoned off.

In the *"flooded" experiment* the soil in the pot was immersed in demineralized water; a 5-cm layer of water was maintained over the surface of the soil.

The soil was treated as described in section 2.1 before it was put into the inner container.

2.4. Greenhouse environment

Cyperus esculentus was grown in a greenhouse from 19 May to 1 July 1981. Average day and night temperatures of the greenhouse were 29.6 and 23.0 ^{o}C, respectively. In the first period of 18 days maximum day temperatures up to 36.9 ^{o}C were observed due to exceptionally bright weather. Relative humidity of the greenhouse varied from 60 to 90%. Average radiation (outside) was 1560 Joules.cm^{-2}. Average day length was 16 hours and 25 minutes.

2.5. Plant species

In the bioassay experiment, the North-American freshwater marsh plant yellow nut sedge, *Cyperus esculentus*, was used. The Waterways Experiment Station provided tubers originating from the same source as the tubers used in the corresponding experiments by Folsom *et al.* (1981).

2.6. *Planting, growing, and harvesting techniques*

Cyperus esculentus propagules (tubers) were germinated between moist paper towels in a warm, dark growth chamber at 37 °C, according to the directions of Dr. John W. Simmers of WES (personal communication). After four days the sprouted tubers were planted in a peat-vermiculite mixture. A photoperiod of 16 hours at 30 °C and a dark period of 8 hours at 23 °C were used.

Because of a mechanical failure in the growth chamber, one portion of tubers did not grow satisfactorily and a new portion of tubers had to be germinated. Consequently, the available *Cyperus* plants at the start of the experiment were rather different and only one large, one medium, and one small sprouted *Cyperus* plant per pot could be planted. This certainly affected later plant growth, as shown by the yields in the separate pots. The aim was to harvest the *Cyperus* plants at maximum vegetative growth, a growing period of 45 days from planting having been suggested. Flowering started in 25% of the plants after 36 days, and a week later 75% of the plants were flowering. The plants were then harvested; all aboveground parts of each pot were collected, rinsed with demineralized water, blotted dry with filter paper, dried to constant weight at 70 °C, and ground to a powder in a food blender modified to avoid heavy-metal contamination.

3. EXPERIMENT WITH ARABLE CROPS

3.1. Soils

For this experiment sediments were selected from the uncontaminated Noordbovenpolder (NP), from the contaminated Spieringpolder (SP), from the dredged material disposal sites Oost Abtspolder (OP) and Broekpolder (BP), and from the Neckar sludge (NS) deposited on land. Table 2 shows characteristics for these substrates.

3.2. Crops

Spring wheat (cv Melchior, 26 seeds per pot) was sown directly in 6-litre pots; radish (cv Cherry Belle, 36 seeds per pot) and red fescue grass (a heavy-metal resistant cv, obtained from the Waterways Experiment Station, Vicksburg, Miss., 0.4 g per pot) were sown directly in 10-litre polyethylene buckets; butterhead lettuce (cv Reskia, 1 plant per pot) was planted in 10-litre polyethylene buckets. Pots were placed in a greenhouse; each crop was treated as a separate experiment. Substrates were given sufficient N, P, K, and Mg as reagent grade chemicals. Plants were watered at least once daily to 70% field capacity with demineralized water. Radish was sown in the pots in which lettuce had grown. When manganese deficiency occurred in spring wheat, a foliar application of a 1.25% $MnSO_4.H_2O$ solution was given. The foliar spray was repeated some three weeks later. Crops were harvested when mature (spring wheat, radish, butterhead lettuce), and grass was cut four times successively when the average height in most pots was about 15 cm. Yield (fresh weight and dry-matter weight) was determined, and samples were taken for analysis for Cu, Zn, Cr, Ni, Pb, and Cd.

4. ANALYTICAL METHODS

4.1. Plant samples

Fresh plant material was washed thoroughly in demineralized water *(Cyperus)* or in a 0.8% Teepol solution in demineralized water. Dry, ripe wheat samples (grain and straw) were not washed. Due care was taken to avoid metal contamination in the procedures of washing, chopping, drying, and grinding of the samples. After washing the excess water was drained, blotted, or centrifuged off, and the samples were dried at 70 °C *(Cyperus)* or 105 °C (other crops). The dried material was ground to a powder in a food blender or in a hammer mill, modified to preclude heavy-metal contamination.

4.2. Digestion and measurement

Samples were wet ashed with H_2SO_4-HNO_3 (for analysis for Cu, Zn, Cr) or with HNO_3 (Pb, Ni, Cd). The elements Cu, Zn, and Cr were estimated in the water phase with atomic absorption flame spectrometry (air-acetylene flame). The elements Cd, Pb, and Ni were subjected to a liquid-liquid extraction procedure to remove most of the interfering matrix elements and to achieve a higher sensitivity. The first extraction removes excess Fe: at pH 3 iron is complexed with 2,4- pentane-dione and removed by extraction with chloroform. After draining off the chloroform layer, pH is raised to 7, and the metals are complexed with sodium diethyldithiocarbamate and extracted with methylisobutylketone (MIBK). The measurement is performed in MIBK-environment with atomic absorption flame spectrometry. All measurements were performed with the Perkin Elmer model 5000 instrument.

4.3. Soil and sediment samples

Soil and sediment samples for analysis for total or DTPA-extractable metals and for physico-chemical characteristics were air dried (temp. 30-40 °C) and crushed in a mill to pass a 2-mm sieve. Due care was taken to preclude heavy-metal contamination during treatments of the samples. Samples for

analysis of DTPA-extractable metals in flooded-soil samples were taken with all precautions necessary to avoid aeration of the sediment. After removal of the plant samples one composite sediment sample per substrate species was obtained by filling a 1-litre glass jar entirely with the anaerobic sediment.

4.4. Digestion and measurement of total metal concentrations of soils and sediments

The metals Cu, Zn, Cr, and Ni were determined by atomic absorption flame spectrometry after digestion with H_2SO_4-HNO_3 (concentrated) 1:1 (and 5 drops of $HClO_4$). For determination of Pb and Cd, the samples were digested with HNO_3 (five times fuming to dryness on a water bath). The digestion methods used did not yield total metal contents of the samples due to the presence of trace metals in the silicate skeleton of the clay minerals that were not dissolved by these relatively mild extractants. In this report we will regard the metal contents determined as total contents. Cr, Cu, and Zn were measured with atomic absorption flame spectrometry in water and Cd, Ni, and Pb after liquid-liquid extraction in MIBK-medium in the same way as in the plant samples.

4.5. Extraction and measurement of DTPA-extractable metals in soils and sediments

The DTPA extracts of soils and sediments were prepared according to the procedure of Lee *et al.* (1978) that is based on that of Lindsay and Norvell (1978).

Extraction of dry, upland sediments and of wet, anaerobic sediments was performed with an equivalent of 25 g of oven-dry sediment in a 250-ml centrifuge bottle. The wet, flooded soil samples were centrifuged first at 13,700 x *g* for 30 minutes to separate the soil from the supernatant interstitial water that was discarded. 125 ml of a 0.005 M DTPA + 0.01 M calcium chloride + 0.1 M triethanolamine (TEA) solution (Lee *et al.*, 1978) buffered at pH 7.3 was added to the sediment remaining in the centrifuge bottle. The bottle was sealed and placed on a shaker for 24 hours; the bottles were then centrifuged as before. The volumes of the resulting

supernatant liquid were measured and the liquid was stored at 4 ^{o}C.

The concentrations of Cu, Zn, Cr, Ni, Pb, and Cd were measured in this solution with atomic absorption flame spectrometry (Perkin Elmer model 5000) and compared with standard solutions of these elements dissolved in the same extractant. Background correction was made.

4.6. *Analysis of macro-constituents*

Organic matter was estimated by oxidation with $K_2Cr_2O_7/H_2SO_4$, whereby excess $K_2Cr_2O_7$ is titrated. $CaCO_3$ was determined according to the gas volumetric method of Scheibler; particle size distribution was determined by the mass pipet method. All methods, including those of pH, P-Al, and KCl, are described in Vierveijzer *et al.* (1979).

5. RESULTS

5.1. Sediments

Origin and physical and chemical characteristics of the selected soils and sediments are presented in tables 1 and 2. All sediments and soils

Table 1. Origin of selected sediments and soils.

origin	code	reclaimed/dredged	year
Noordbovenpolder	NP	sedimented in situ, reclaimed in polder	1780
Spieringpolder	SP	sedimented in situ, reclaimed in polder	1953
Oostabtspolder	OP	dredged from Rotterdam harbour	1974
Broekpolder	BP	dredged from Rotterdam harbour	1975
Neckar sludge	NS	dredged from lock in Neckar river	1979
WES reference soil	WS	lake sediment from Vicksburg, Miss., USA	1981

originate from the same river basins of the rivers Rhine and Meuse, and have similar properties and texture. Differences exist in the macro- and micronutrient status. The common origin and corresponding properties of the sediments may be advantageous in obtaining good soil-plant correlations for the heavy metals.

Table 2. Physical and chemical characteristics of the sediments (dry-matter basis).

origin code	organic matter	$CaCO_3$	particle size				pH 1)	P-Al 2)	K 3)
			< 2 µm	< 16 µm	< 50 µm	> 210 µm			
	%	%	%	%	%	%		mg/100 g	mg/100 g
NP	5.1	8.1	29.3	48.7	75.1	0.5	7.02	24	12
SP	6.5	8.6	27.2	48.3	62.4	8.8	7.20	39	20
OP	10.1	12.8	31.0	51.5	72.2	0.7	7.08	100	36
BP	9.7	15.2	27.7	51.7	65.0	1.6	7.13	102	67
NS	7.4	15.7	28.3	45.6	64.6	2.6	7.14	129	23

1) pH in 1 M KCl (1:5 soil/solution ratio).

2) ammonium lactate soluble phosphate (1:10 soil/solution ratio).

3) 0.1 HCl-soluble K (1:10 soil/solution ratio).

A wide range in heavy-metal contamination is shown in the selected sediments. This is particularly true for the toxic metal cadmium, its concentration ranging from 0.5 - 40 $mg.kg^{-1}$ (table 3). The substrates were used under aerated and anaerobic (flooded) conditions. Flooded conditions were obtained by immersing the soil and maintaining a layer of about 5 cm of water over the soil surface. An incubation period of 3 - 7 weeks may be insufficient to attain a new physical, chemical, and microbial equilibrium in the substrate (see page 6). This should be kept in mind when comparing the results presented here with those of Folsom *et al.* (1981) for the flooded soil.

The data presented in table 4 indicate the effect of flooding on the DTPA-extractable metals. The extractability of most metals decreases as a result of flooding, but the differences between aerated and flooded soils are smaller than those reported by Folsom *et al.* (1981). The ratio of DTPA-extractable to total metals (table 5) reflects the mobilizable fraction of the metals in the sediment, and may be associated with the plant-available fraction. The DTPA-extractable/total metal ratio is extremely low for Cr (0.001) and increases in the order Ni < Pb < Zn < Cu < Cd (Cd flooded: 0.08 - 0.42, Cd upland:0.39 - 0.58). In most sediments the ratios under upland conditions tend to be somewhat higher than under flooded conditions. In the section on plant heavy-metal uptake the significance of the DTPA extraction will be discussed.

5.2. *Cyperus esculentus experiment*

The *Cyperus* experiment was conducted on four substrates (table 1), viz., an old uncontaminated fluvial clay from the Noordbovenpolder (NP), a contaminated fluvial clay from the Spieringpolder (SP), and two contaminated sediments obtained from dredged material disposal sites: Oostabtspolder (OP) and Broekpolder (BP). As disposal sites are generally not fertilized, no nutrients were added to these sediments. A reference soil, supplied by the Waterways Experiment Station (Vicksburg, Miss., USA), was included in the experiment. This soil is very poor in nutrients and received a basal dressing of N, P, K, and Mg. The WES reference soil was included in order to compare *Cyperus* growth and appearance on various substrates under the specific

Table 3. Total heavy-metal concentrations in sediments (dry-matter basis).

origin code	Cu	Zn	Cr	Ni	Pb	Cd	Hg	As
					$mg.kg^{-1}$			
NP	26	115	101	40	42	0.57	0.18	14.6
SP	112	998	169	46	271	5.35	2.28	35.8
OP	129	777	320	50	191	11.9	0.32	27.1
BP	211	1296	496	58	341	21.0	5.89	38.1
NS	269	726	611	75	210	41.4	nd	nd
WS	14	51	60	19	10	0.07	nd	nd

nd = not determined.

Table 4. Concentrations of heavy metals in DTPA extracts of flooded and upland sediments (dry-matter basis).

origin	Cu		Zn		Cr		Ni		Pb		Cd	
code	flooded	upland	flooded	upland	flooded	upland	flooded	upland	flooded	upland	flooded	upland
	mg.kg^{-1}											
NP	5.6	5.4	6.0	10.2	bd	bd	2.69	2.19	6.4	7.2	bd	0.33
SP	44.3	41.0	101	162	bd	bd	2.34	2.66	42.7	68.1	2.25	2.85
OP	38.9	45.5	133	211	0.095	0.090	4.13	5.73	8.6	24.0	3.67	5.38
BP	25.1	78.6	247	365	0.259	0.133	3.82	5.58	7.0	23.9	5.03	8.16
NS	nd	131	nd	217	nd	0.137	nd	11.6	nd	49.4	nd	19.7
WS	0.8	0.7	0.5	0.7	bd	bd	0.20	0.26	2.0	0.9	bd	0.09

bd = below detection limit of 0.05 mg.kg^{-1}.

nd = not determined.

Table 5. Average ratio between DTPA-extractable and total metals in *sediments*.

origin	Cu		Zn		Ni		Pb		Cd	
code	flooded	upland	flooded	upland	flooded	upland	flooded	upland	flooded	upland
NP	0.21	0.21	0.052	0.089	0.067	0.055	0.15	0.17	0.081	0.58
SP	0.40	0.37	0.10	0.16	0.051	0.058	0.16	0.25	0.42	0.53
OP	0.30	0.35	0.17	0.27	0.082	0.11	0.045	0.13	0.31	0.45
BP	0.12	0.37	0.19	0.28	0.066	0.097	0.021	0.07	0.24	0.39
WS	0.056	0.055	0.01	0.014	0.011	0.014	0.20	0.084	<0.76	1.30
NS	nd	0.49	nd	0.30	nd	0.15	nd	0.24	nd	0.48

The ratio DTPA/total Cr was < 0.001 for all sediments.

nd = not determined.

Dutch growing conditions. The plant material grown on the WES reference was not analyzed for heavy metals.

5.2.1. Plant growth

Cyperus performed well, both on flooded and upland substrates (table 6, appendixes A and B). Differences in yield may be due to different nutrient levels of the substrates, but there is no obvious relationship (table 2). Neither is there a relationship between yield and heavy-metal status of the substrates, whether expressed as total or as DTPA-extractable metals (table 4). The highest 'upland' yield was obtained on the most contaminated sediment (BP).

Table 6. Average yield and dry-matter contents of *Cyperus esculentus*.

origin code	yield g dry matter.pot^{-1}		dry matter content	
			%	%
	flooded	upland	flooded	upland
NP	21.1	28.7	24.4	22.8
SP	16.2	20.5	22.1	27.0
OP	13.4	14.6	22.7	26.4
BP	17.8	35.5	23.0	23.9
WS	22.7	30.0	22.9	27.1

5.2.2. Crop chemical composition

Chemical data on the above-ground tissues of *Cyperus esculentus* are presented in table 7 and appendixes A and B. Under upland conditions *Cyperus* contained more Cd, Cu, Ni, and Zn than under flooded conditions. The Cr concentrations were all below the detection limit. *Cyperus* grown on contaminated sediments contained more Cd and Zn than the crop on the uncontaminated fluvial clay from the Noordbovenpolder, both under upland and flooded conditions.

Table 7. Average heavy-metal concentrations in *Cyperus esculentus* (dry-matter basis).

origin code	Cu flooded	Cu upland	Zn flooded	Zn upland	Ni flooded	Ni upland	Pb flooded	Pb upland	Cd flooded	Cd upland
	$mg.kg^{-1}$									
NP	6.1	12.1	34	78	0.35	0.95	0.63	0.19	0.16	0.65
SP	11.1	11.7	47	99	0.40	0.45	0.83	0.32	0.62	1.43
OP	7.4	11.9	47	132	0.51	0.63	0.56	0.28	0.86	3.36
BP	7.6	12.3	37	132	0.51	0.66	0.36	0.24	0.95	4.75

Chromium concentrations were below detection limit (0.25 $mg.kg^{-1}$) in all samples.

5.2.3. *Soil-plant correlations*

From four extraction procedures for dredged sediments, Lee *et al.* (1978) selected the DTPA-TEA-$CaCL_2$ (pH 7.3) procedure. This procedure was also followed in this study.

In figures 1A and 1B total and DTPA-extractable cadmium have been plotted against plant cadmium. Both total and DTPA-extractable Cd, under upland and flooded conditions, are positively related to plant Cd, but the differences between 'upland' and 'flooded' *Cyperus* Cd levels remain. The relationship between substrate and plant Zn is shown in figures 2A and 2B. Under flooded conditions there is no relation between plant Zn and substrate total Zn or DTPA-extractable Zn. Under 'upland' conditions a positive relationship exists between plant Zn and total Zn, especially DTPA-extractable Zn. Soil-plant correlations are less pronounced for Ni and absent for Cu and Pb. The relevant linear correlation coefficients

Cyperus esculentus

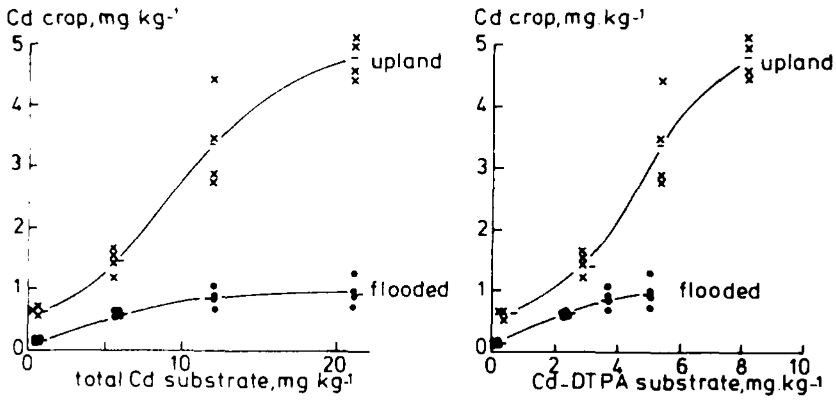


Fig. 1A Relationship between total Cd in the substrates and in the leaves of *Cyperus esculentus* (flooded and upland).

Fig. 1B Relationship between DTPA-extractable Cd in the substrates and in the leaves of *Cyperus esculentus* (flooded and upland).

r^2 are given in appendix L. Substrate metal concentrations can also be related to total uptake per pot of plant metal, in the case of *Cyperus* of the above-ground plant material. The relevant linear correlation coefficients r^2 in appendix M are much lower than those for plant metal concentrations in appendix L.

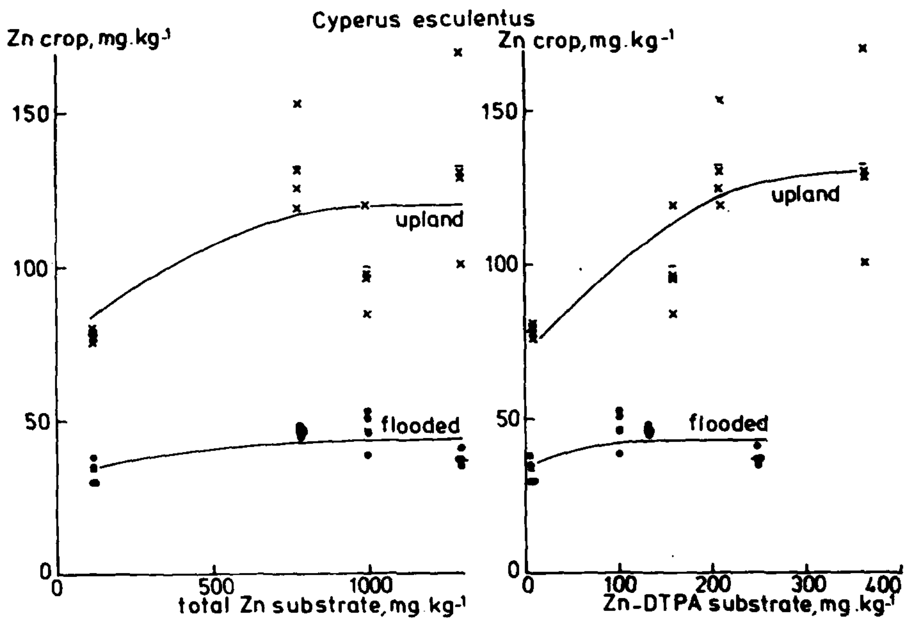


Fig. 2A Relationship between total Zn in the substrates and in the leaves of *Cyperus esculentus* (flooded and upland).

Fig. 2B Relationship between DTPA-extractable Zn in the substrates and in the leaves of *Cyperus esculentus*.

5.2.4. Comparison of the experimental results with those of Folsom et al. (1981)

In the experiments reported herein, the same clonal plant material and the same double-bucket plant containers were used as described by Folsom *et al.* (1981).

The main differences were:

* *Pretreatment of sediment samples* (see page 6). Folsom used anaerobic dredged material that remained anaerobic in the 'flooded' part of the experiment. Upland conditions were obtained by drying and grinding the anaerobic sediments. This material is not likely to behave as normal aerated upland soil.

By contrast, in our experiments, the sediments selected for *Cyperus* cultivation had been aerobic for at least seven years, and in most cases much longer. Although organic matter content is relatively high, the upland sediments may be considered normal aerated soils. Flooded conditions were obtained by immersing the aerobic sediments and incubating them for eight weeks. It is not likely that a steady, anaerobic state was attained.

* *Maximum vegetative growth period* of *Cyperus* in our experiments was 45 days and in Folsom's experiments 90 days. In both experiments part of the plants were flowering when harvested. The duration of the vegetative period is probably affected by day length.
* *Sediments*. The sediments selected for our experiments were much more similar in physicochemical nature and degree of contamination than those in Folsom's experiments.
* *Growth*. In our experiments, in contrast to Folsom's data, yields of aboveground parts were higher under upland than under flooded conditions.
* *Plant uptake of heavy metals*. Because of large differences in sediments and growing conditions, it is difficult to compare plant heavy-metal concentrations. Most levels are of the same magnitude, except for the higher Cu and lower Pb levels under upland conditions in our experiments.

In our experiments the higher concentrations of Cd, Cu, Ni, and Zn in plants grown in upland sediments as compared with flooded sediments could not be explained by a decrease in plant growth. In Folsom's experiments the higher Cd, Cu, Cr, Mn, Pb, and Zn concentrations in plants grown in upland sediments were attributed to reduced plant growth.

In spite of the differences in experimental conditions, *Cyperus* was found to be an effective indicator of contamination of dredged material with Cd and Zn.

5.3. Experiments with lettuce, radish, spring wheat, and red fescue grass

The crop experiments were performed on five substrates (table 1), i.e. four substrates also used in the *Cyperus* experiment and a heavily contaminated dredged material (NS) from a disposal site near the river Neckar, a tributary of the river Rhine. All substrates received a basal dressing

of N, P, K, and Mg according to the specific needs of the crops. The WES soil was not included in these experiments.

5.3.1. Plant growth

Most crops performed well on the contaminated sediments (table 8, appendixes C-K). Yields differed among substrates, but were not found to be related to contaminants or to macronutrients (tables 2 and 3). On the uncontaminated substrate, lettuce attained only 10% of the average yield produced on the contaminated substrates. Radish yielded more on uncontaminated than on the contaminated substrates. These anomalies may be due to specific needs of these crops that are not met by the substrates. Spring wheat performed equally well on all substrates, but the crops on the contaminated substrates showed slight to severe symptoms of Mn deficiency. The disorder was controlled by two foliar sprays of manganous sulphate. Without this treatment a severe yield depression would occur (Smilde and Van Driel, 1977). Growth of red fescue grass was relatively poor; plant stand was thin on all substrates. Leaf colour was normal. Red fescue grass is known to be a slow growing species.

5.3.2. Crop chemical composition

Data on the chemical composition of the investigated plant tissues are presented in tables 9-11 and appendixes C-K. All crops grown on contaminated sediments contained more Cd than did crops on uncontaminated fluvial clay. This also applies to Zn, Ni, and Cu (except in grass), to Cr in radish tuber and leaf, and to Pb in lettuce, radish leaf, and spring wheat (straw).

5.3.3. Soil-plant correlations

Correlations between soil (total and DTPA-extractable) Cd, Zn, and Ni and the respective crop concentrations are shown in figures 3, 4, and 5, respectively. Cd accumulated especially in radish and lettuce foliage, and to a lesser extent in radish tubers and wheat straw. DTPA-extractable Cd is slightly better related to plant Cd than is total substrate Cd. The relevant linear correlation coefficients r^2 are given in appendix L. Figure 3 shows that the relationships are not always linear. In this experiment soil-plant correlations for Zn and Ni (figures 4 and 5) may be considered linear. DTPA extraction clearly improved the soil-plant correlations for Zn, but not for Cd and Ni. Plant Cr and Pb, that accumulate in the roots, were not related to substrate total or DTPA-extractable metals.

Table 8. Average yield (g dry matter.pot^{-1}) and dry-matter content (%) of lettuce, radish, spring wheat, and red fescue grass.

origin code	butterhead lettuce		radish				spring wheat			
			tuber		leaf		grains		straw	
	yield	dry matter	yield	dry matter	yield	dry matter	yield	dry matter	yield	dry matter
NP	1.10	10.5	6.76	6.4	11.83	7.7	52.52	91.4	51.57	86.5
SP	8.38	5.4	4.16	5.4	10.79	6.1	51.33	89.0	52.20	89.0
OP	11.22	5.2	3.50	5.9	10.18	6.6	44.17	88.8	47.90	88.3
BP	10.00	5.5	2.75	5.5	9.95	6.4	39.15	89.0	47.42	88.4
NS	12.19	5.6	3.51	5.4	10.17	6.5	49.17	89.0	48.42	88.6

origin code	red fescue grass (leaves)							
	1st cut		2nd cut		3rd cut		4th cut	
	yield	dry matter	yield	dry matter	yield	dry matter	yield	dry matter
NP	5.89	16.6	4.34	16.8	6.16	17.9	4.83	18.4
SP	7.55	15.3	6.37	16.8	5.74	18.7	5.61	20.5
OP	5.99	14.0	6.80	15.1	8.92	17.8	8.17	18.7
BP	4.17	14.7	4.28	14.4	4.48	16.1	4.56	17.8
NS	7.83	14.5	9.46	15.8	9.49	17.1	7.37	19.6

Table 9. Average copper and zinc concentrations in crops (dry-matter basis).

copper

origin	lettuce	radish		spring wheat		red fescue grass			
code		tuber	leaves	grains	straw	1^{st} cut	2^{nd} cut	3^{rd} cut	4^{th} cut
	mg.kg^{-1}								
NP	6.1	3.9	4.8	8.1	3.6	16.0	17.5	12.1	10.9
SP	11.6	7.6	6.6	7.2	3.4	18.3	16.5	12.3	11.8
OP	10.9	7.7	5.6	7.4	3.9	18.8	18.1	12.2	10.6
BP	11.7	12.0	9.0	9.9	4.8	18.9	20.6	13.2	12.9
NS	11.0	16.7	13.1	10.4	6.4	19.6	18.1	13.4	12.6

zinc

NP	55	30	75	56	22	43	34	36	33
SP	73	73	94	68	73	41	27	30	34
OP	84	92	105	88	99	46	30	34	29
BP	131	138	185	110	168	44	34	34	37
NS	119	124	172	98	97	58	37	40	40

Table 10. Average chromium and nickel concentrations in crops (dry-matter basis).

chromium

origin code	lettuce	radish tuber	radish leaves	spring wheat grains	spring wheat straw	red fescue grass (leaves) 1^{st} cut	2^{nd} cut	3^{rd} cut	4^{th} cut
					$mg.kg^{-1}$				
NP	1.52	1.61	1.20	bd	bd	bd	0.83	0.73	0.91
SP	1.11	4.23	1.35	bd	bd	bd	0.84	0.41	0.77
OP	1.02	3.88	1.27	bd	bd	bd	0.69	0.57	†
BP	1.07	6.52	1.61	bd	bd	bd	0.62	0.88	0.78
NS	1.19	6.65	1.46	bd	bd	bd	0.63	0.66	0.70

bd = below detection limit of 0.25 $mg.kg^{-1}$.
† = inconsistent analytical results.

nickel

NP	0.45	0.34	0.29	0.08	0.18	1.98	1.37	1.59	1.31
SP	0.39	0.98	0.33	0.16	0.30	0.87	0.71	0.65	0.57
OP	0.56	1.08	0.46	0.33	0.33	1.82	0.88	1.02	0.72
BP	0.73	1.69	0.96	0.48	0.46	2.28	1.47	1.35	1.42
NS	1.47	3.95	2.11	0.72	0.33	5.35	3.60	3.29	2.88

Table 11. Average lead and cadmium concentrations in crops (dry-matter basis).

lead

origin	lettuce	radish		spring wheat		red fescue grass (leaves)			
code		tuber	leaves	grains	straw	1st cut	2nd cut	3rd cut	4th cut
	$mg.kg^{-1}$								
NP	0.68	bd	0.58	0.09	1.16	0.33	0.63	+	0.98
SP	0.88	3.50	1.35	0.11	1.37	0.49	0.56	+	1.06
OP	0.84	2.53	1.07	0.17	1.53	1.10	0.60	+	0.97
BP	0.70	4.68	1.83	0.09	1.69	0.64	0.94	+	+
NS	0.72	4.45	1.21	0.16	1.56	0.52	0.58	+	0.80

+ = inconsistent analytical results.
bd = below detection limit of 0.10 $mg.kg^{-1}$.

cadmium

NP	1.89	0.17	0.66	0.12	0.24	0.43	0.30	0.28	0.28
SP	2.03	0.82	2.34	0.26	0.56	0.70	0.48	0.45	0.53
OP	4.13	1.88	3.67	0.61	1.18	1.18	1.18	1.11	1.08
BP	7.70	3.11	6.47	0.68	1.44	1.13	1.17	1.17	1.24
NS	24.2	10.5	33.6	2.29	5.52	3.76	3.33	3.01	3.38

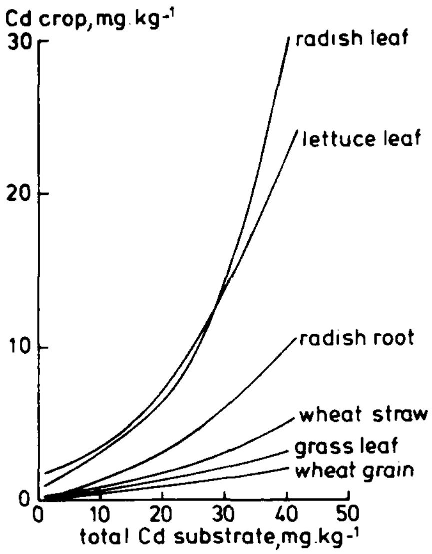


Fig. 3A Relationship between total Cd in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

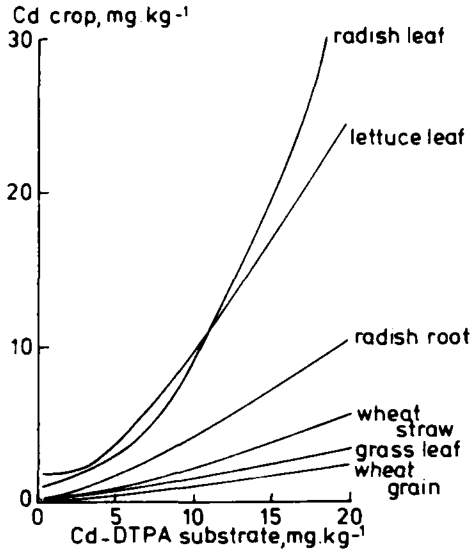
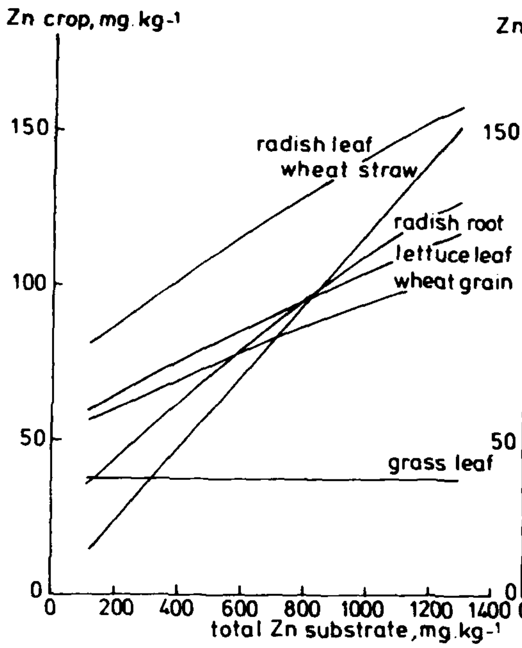


Fig. 3B Relationship between DTPA-extractable Cd in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

Substrate metal concentrations also can be related to total uptake of plant metal per pot, in the case of *Cyperus* of the above ground plant material. The relevant linear correlation coefficients r^2 in appendix M are much lower than those for plant metal concentrations in appendix L. DTPA extraction improved the soil-plant relationship for Cd and Zn, but not for the other elements. Use of plant-metal uptake instead of plant-metal concentration does not give a better soil-plant relationship.



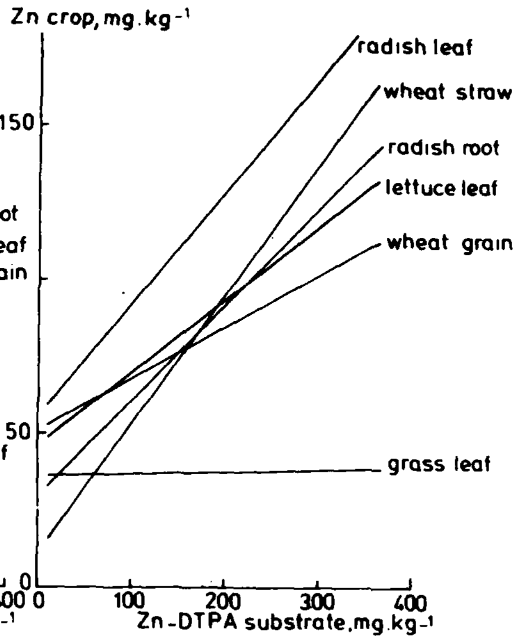


Fig. 4A Relationship between total Zn in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

Fig. 4B Relationship between DTPA-extractable Zn in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

Red fescue grass seed supplied by the Waterways Experiment Station was from a heavy-metal-resistant variety commonly used on bare mine tailings where other plant species are unable to survive.

Uptake of heavy metals except Cd by red fescue grass in this experiment was relatively low. Accumulation was clearly demonstrated by the 'accumulation factors' for the various elements, i.e. the mean concentration in the grass grown on the contaminated substrates divided by the mean concentration in the grass on the uncontaminated reference soil. The 'accumulation factors' were compared with those obtained in a pot experiment with English ryegrass, cultivated both on dredged material and on refer-

ence soils (Van Driel *et al.*, 1977). The average 'accumulation factors' for red fescue grass and English ryegrass are, respectively: 1.1 and 2.5 for Cu, 1.02 and 3.6 for Zn, 1.2 and 1.7 for Ni, 0.8 and 2.3 for Cr, 1.4 and 1.5 for Pb, and 4.9 and 4.5 for Cd. In this experiment no accumulation of Cr, Cu, Ni, and Zn took place in red fescue, but Cd and Pb were accumulated at the same rate as in English ryegrass.

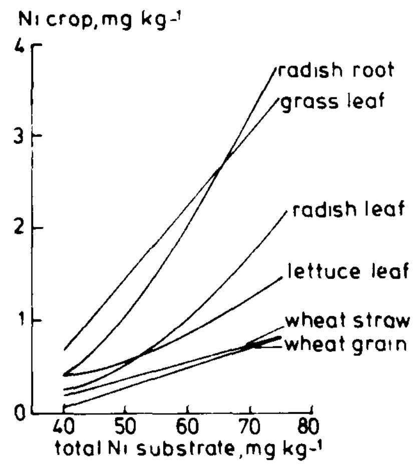


Fig. 5A Relationship between total Ni in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

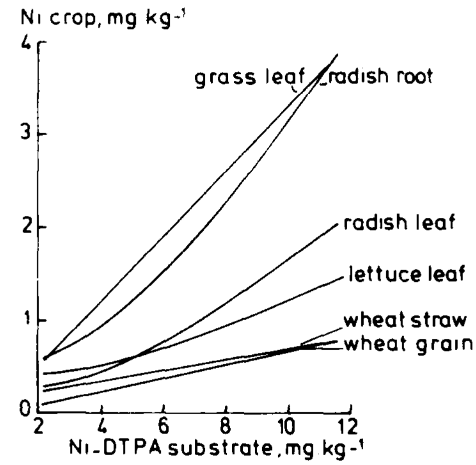


Fig. 5B Relationship between DTPA-extractable Ni in the substrates and in lettuce, radish, spring wheat, and red fescue grass.

6. DISCUSSION

6.1. Health aspects

Standards have been set by WHO-FAO for heavy-metal contaminants considered hazardous to human health, the so-called acceptable daily intake (ADI); it amounts to 65 and 430 µg for Cd and Pb, respectively (World Health Organization, 1972). These ADI's may be translated into guidelines for maximum heavy-metal concentrations in foodstuffs, taking into account the variation in native heavy-metal concentrations of the diet constituents and the composition of the diet.

Tentative maxima for Cd and Pb in some foodstuffs are: 0.1 $mg.kg^{-1}$ Cd in leafy vegetables, potatoes, and cereals, and 0.05 $mg.kg^{-1}$ Cd in root vegetables; 0.1 $mg.kg^{-1}$ Pb in root vegetables and cereals, 1.2 $mg.kg^{-1}$ Pb in leafy vegetables (Anonymous, 1979). All these concentrations are on a fresh weight basis. In figure 6, Cd concentrations of consumable crops have been plotted against total and DTPA-extractable soil Cd. The horizontal, dashed line (-----) is the proposed limit of 0.1 $mg.kg^{-1}$ for most

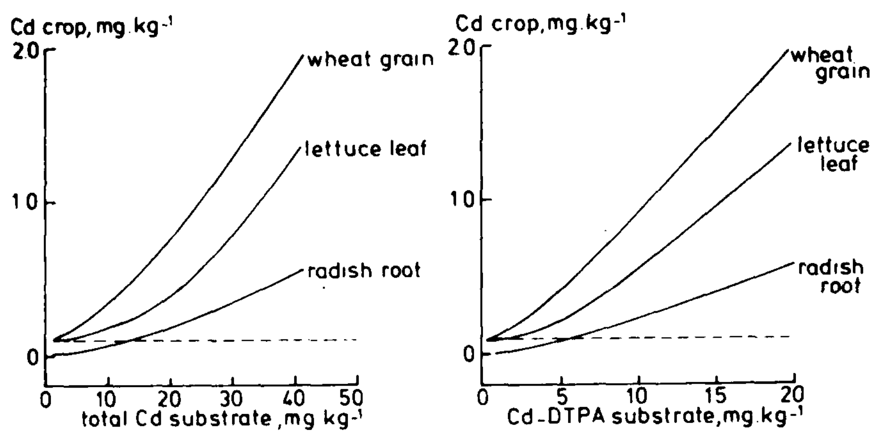


Fig. 6 Cd concentrations ($mg.kg^{-1}$ fresh weight) of edible parts of lettuce, radish, and spring wheat as related to the total and DTPA-extractable Cd of the substrate. Dashed line (----) is the provisional guideline of 0.1 $mg.kg^{-1}$ (fresh weight) for Cd in vegetables.

products. Wheat grain, lettuce and radish tubers grown on contaminated river sediments exceed these tentative maxima.

Maximum concentrations of some elements in feeds have been established for Cu (20 $mg.kg^{-1}$, Dutch Ministry of Agriculture, 1973) and for Pb (10, 5, and 40 $mg.kg^{-1}$ for single feed, mixed feed, and roughage, respectively; European Community, 1974). The following levels have been proposed for Cd: 0.5, 1.0, and 1-2 $mg.kg^{-1}$ for single feed, mixed feed, and roughage, respectively (unofficial Dutch source). All concentrations in feeds are on a 12% moisture basis. Cu and Pb in wheat grain, wheat straw, *Cyperus* leaves,and grass do not exceed the limits for feeds. Cd concentrations in these crops exceed the tentative limits for single feeds and roughage on most substrates.

6.2. Use of results with Cyperus for estimating effects on agronomic crops

Bioassay of dredged material, using *Cyperus esculentus* as the test plant, gives relevant information on the accumulation of heavy metals in the ecosystem. It may be useful to predict effects on commercial crops from the *Cyperus* data, particularly fo.: Cd, the element that accumulates strongest and is the most toxic. The relationship between the heavy-metal status of *Cyperus esculentus* and that of the commercial crops can be expressed on the basis of metal concentrations or total metal uptake. In figure 7 Cd concentrations of various crops have been plotted against *Cyperus* Cd concentrations. A corresponding figure can be obtained using Cd uptake of the specified plant parts and the above ground parts of *Cyperus*. Linear correlation coefficients (r^2) for these regressions are given in appendix N.

These regressions indicate a good potential for using *Cyperus esculentus* as an indicator species to predict Cd uptake by commercial crops cultivated on contaminated sediments. In these experiments both plant Cd concentrations and Cd uptake per pot give good correlations, Cd concentrations being superior. The correlations for the other metals are much lower. However, these regressions have been derived from controlled greenhouse pot experiments with only one type of sediment, heavy calcareous fluvial clay, and need to be verified under field environments and with various sediment types. Field verification studies are in progress at the Institute for Soil Fertility, but it may be several years before results become available.

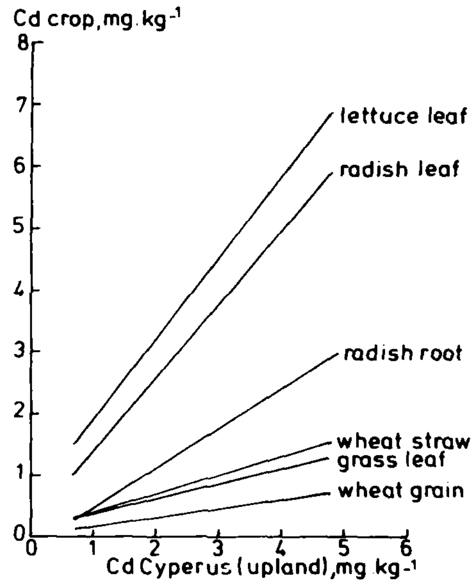


Fig. 7 Relationship between Cd in *Cyperus* leaves (upland) and in lettuce, radish, spring wheat, and red fescue grass.

7. SUMMARY

A series of pot experiments was conducted including:

* a bioassay with the marsh plant *Cyperus esculentus* on aerated (upland) substrates.
* a bioassay with *Cyperus esculentus* on reduced (flooded) substrates.
* pot experiments with lettuce (*Lactuca sativa* L.), radish (*Raphanus sativus* L.), spring wheat (*Triticum aestivum* L.), and a heavy-metal resistant variety of red fescue grass (*Festuca rubra* L.).

Substrates selected were contaminated, heavy fluvial clay soils originating from the river Rhine or tributaries, sedimented in situ, or dredged from the Rotterdam harbour and deposited at a disposal site under aerobic conditions. An uncontaminated fluvial clay was included as a reference soil.

All plant species performed well, both on uncontaminated and on contaminated substrates.

Under upland conditions, *Cyperus esculentus* accumulated more Cd, Cu, Ni, and Zn, and less Pb than under flooded conditions. On contaminated substrates, *Cyperus* contained more Cd and Zn than on the reference fluvial clay soil, both under upland and flooded conditions. The results of the plant bioassay with *Cyperus* on dredged material agree reasonably well with those of Folsom *et al.* (1981), although differences in sediment pretreatment and in cultivation methods resulted in some deviations.

Cd, Ni, Pb, and Zn accumulated in nearly all crops cultivated on contaminated substrates. Only in red fescue was accumulation limited to Pb and Zn. There was no response to the increased concentrations of the other metals in the substrate.

Good correlations between substrate (total) and plant (foliar) metal concentrations were found to exist for Cd and Zn in all crops except grass, and in lettuce and spring wheat for Ni. DTPA-extractable metal correlated as well as substrate total metal with plant metal concentration for all metals and was better correlated with plant Zn than total.

Cd concentrations in consumable products and feeds grown on contaminated river sediments exceeded the tentative maximum values for these products. Cu and Pb remained well under the limits for feeds in all products. The concentrations of the other metals examined were considered to be harmless.

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9. APPENDIXES

Appendix A-K Complete results of pot experiments

A Heavy-metal concentration and yield of *Cyperus esculentus* (flooded)

B Heavy-metal concentration and yield of *Cyperus esculentus* (upland)

C Heavy-metal concentration and yield of lettuce

D Heavy-metal concentration and yield of radish tuber

E Heavy-metal concentration and yield of radish leaves

F Heavy-metal concentration and yield of spring wheat grain

G Heavy-metal concentration and yield of spring wheat straw

H Heavy-metal concentration and yield of red fescue grass 1st cut

I Heavy-metal concentration and yield of red fescue grass 2nd cut

J Heavy-metal concentration and yield of red fescue grass 3rd cut

K Heavy-metal concentration and yield of red fescue grass 4th cut

L Linear correlation coefficients (r^2) for total and DTPA-extractable heavy metals from sediments versus plant heavy-metal concentrations of *Cyperus esculentus* and some agronomic plant species

M Linear correlation coefficients (r^2) for total and DTPA-extractable heavy metals from sediments versus total uptake (concentration x yield) of heavy metals by *Cyperus esculentus* and some agronomic plant species

N Linear correlation coefficients (r^2) for *Cyperus* heavy-metal concentrations versus crop metal concentrations (conc.), and for *Cyperus* heavy-metal uptake per pot versus crop heavy-metal uptake per pot (upt.)

Appendix A

Heavy-metal concentration and yield of *Cyperus esculentus* (flooded).

Sediment: Noordbovenpolder, code NP

pot no.	Cu	Zn	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
3	6.6	38	0.39	0.33	0.18	16.1	22.9
9	5.3	30	0.38	0.65	0.15	24.6	25.9
15	6.6	35	0.32	0.71	0.15	18.8	25.7
17	5.7	30	0.32	0.82	0.16	24.7	23.0
$\bar{x}$	6.1	34	0.35	0.63	0.16	21.1	24.4
s	0.7	4	0.04	0.21	0.01	4.3	1.7

Sediment: Spieringpolder, code SP

5	10.7	46	0.43	0.59	0.59	17.7	23.2
7	11.8	53	0.33	1.43	0.64	16.5	21.4
12	11.2	39	0.44	0.44	0.59	13.7	20.9
18	10.6	51	0.40	0.85	0.65	16.8	23.0
$\bar{x}$	11.1	47	0.40	0.83	0.62	16.2	22.1
s	0.6	6	0.05	0.44	0.03	1.7	1.2

Sediment: Oostabtspolder, code OP

4	7.5	45	0.66	0.33	0.85	12.9	23.1
6	7.7	46	0.44	0.60	0.67	16.3	23.7
13	7.2	48	0.58	0.44	0.88	14.0	22.5
19	7.3	46	0.37	0.85	1.05	10.6	21.5
$\bar{x}$	7.4	47	0.51	0.56	0.86	13.4	22.7
s	0.2	1	0.13	0.23	0.16	2.4	0.9

Sediment: Broekpolder, code BP

2	7.4	35	0.53	0.48	0.71	18.9	23.6
8	7.4	37	0.44	0.33	0.90	16.3	22.0
14	7.8	37	0.64	0.33	0.91	17.4	23.0
16	7.7	41	0.44	0.28	1.27	18.5	23.3
$\bar{x}$	7.6	37	0.51	0.36	0.95	17.8	23.0
s	0.2	3	0.10	0.09	0.23	1.2	0.7

Chromium concentration was in all samples below the detection limit of 0.25 $mg.kg^{-1}$.

Appendix B

Heavy-metal concentration and yield of *Cyperus esculentus* (upland).

Sediment: Noordbovenpolder, code NP

pot no.	Cu	Zn	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
24	12.3	77	0.97	0.22	0.69	22.4	23.0
27	12.1	79	1.02	0.11	0.59	29.7	22.1
32	12.2	76	0.93	0.22	0.64	22.3	23.1
38	11.8	80	0.87	0.22	0.66	40.3	23.1
$\bar{x}$	12.1	78	0.95	0.19	0.65	28.7	22.8
s	0.2	2	0.06	0.06	0.04	8.5	0.5

Sediment: Spieringpolder, code SP

23	12.7	119	0.60	0.39	1.40	15.2	27.6
29	11.8	96	0.49	0.38	1.62	23.3	25.0
34	11.7	95	0.32	0.32	1.50	23.0	26.9
37	10.4	84	0.39	0.17	1.19	20.5	28.6
$\bar{x}$	11.7	99	0.45	0.32	1.43	20.5	27.0
s	1.0	15	0.12	0.10	0.18	3.8	1.5

Sediment: Oostabtspolder, code OP

25	13.2	153	0.68	0.11	4.41	15.8	24.6
26	12.3	130	0.66	0.28	3.42	15.0	24.9
33	11.8	125	0.65	0.44	2.88	13.2	27.9
39	10.4	119	0.51	0.28	2.74	14.3	28.3
$\bar{x}$	11.9	132	0.63	0.28	3.36	14.6	26.4
s	1.2	15	0.08	0.13	0.76	1.1	1.9

Sediment: Broekpolder, code BP

22	12.1	128	0.60	0.22	5.09	30.2	24.6
28	11.8	130	0.63	0.21	4.44	37.4	24.6
35	13.8	169	0.88	0.21	4.92	38.9	23.4
36	11.3	100	0.54	0.33	4.55	35.6	23.0
$\bar{x}$	12.3	132	0.66	0.24	4.75	35.5	23.9
s	1.1	28	0.15	0.06	0.31	3.8	0.8

Chromium concentration was in all samples below the detection limit of $0.25\ mg.kg^{-1}$.

Appendix C

Heavy-metal concentration and yield of lettuce.

Sediment: Noordbovenpolder, code NP

pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
				$mg.kg^{-1}$			$g.pot^{-1}$	%
44							0.89	9.1
47							0.98	11.2
51							2.62	7.3
60	the analysis has been performed in a composite sample						0.65	13.7
62							0.80	6.9
69							0.59	12.0
74							1.59	6.5
77							0.69	17.7
$\bar{x}$	6.1	55	1.52	0.45	0.68	1.89	1.10	10.5
s							0.69	3.9

Sediment: Spieringpolder, code SP

pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
43	10.9	72	1.55	0.45	5.73 +)	2.34	7.59	5.52
46	9.0	67	1.16	0.33	0.66	2.10	8.71	5.56
54	16.4	84	1.63	0.34	1.24	1.94	9.07	5.11
56	15.8	74	1.20	0.22	1.00	2.12	7.09	5.35
61	10.5	71	0.89	0.56	0.56	1.88	9.20	5.38
68	10.2	72	0.86	0.45	0.68	1.93	8.81	5.54
71	10.4	73	0.66	0.46	0.57	1.72	8.97	5.15
78	9.8	73	0.91	0.34	1.48	2.19	7.63	5.37
$\bar{x}$	11.6	73	1.11	0.39	0.88	2.03	8.38	5.37
s	2.8	5	0.34	0.11	0.36	0.20	0.81	0.17

+) excluded from calculation of mean values.

Sediment: Oostabtspolder, code OP

pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
45	12.4	88	1.42	0.42	0.63	3.96	10.8	5.23
49	9.9	76	0.65	0.68	0.90	4.59	13.2	5.13
55	10.2	78	1.15	0.45	0.90	4.50	12.2	5.20
57	10.0	79	1.19	0.66	0.22	4.27	10.9	5.26
64	11.6	87	1.26	0.68	1.58	3.73	10.6	5.26
70	10.9	86	1.04	0.45	0.45	3.82	11.9	5.09
72	11.0	90	0.86	0.68	0.68	4.17	10.2	5.16
80	11.2	87	0.55	0.45	1.36	3.97	10.0	5.47
$\bar{x}$	10.9	84	1.02	0.56	0.84	4.13	11.2	5.22
s	0.9	5	0.30	0.12	0.45	0.31	1.1	0.12

Sediment: Broekpolder, code BP

pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
41	15.6	135	1.17	0.90	0.67	7.83	10.2	5.63
50	9.6	113	1.55	0.66	0.22	7.86	10.1	5.55
53	11.7	129	2.34	0.90	0.90	9.42 x)	11.0	5.32
59	12.7	126	0.97	0.67	0.67	7.84	8.6	5.79
65	11.3	126	0.59	0.67	0.67	7.72	10.4	5.33
67	10.9	136	0.81	0.68	0.68	7.14	10.9	5.36
75	10.1	143	0.79	0.68	1.13	7.71	10.2	5.34
76	11.8	137	0.34	0.68	0.68	7.83	8.7	5.42
$\bar{x}$	11.7	131	1.07	0.73	0.70	7.70	10.0	5.47
s	1.9	9	0.63	0.11	0.26	0.26	0.9	0.17

Sediment: Neckar sludge, code NS

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
				$mg.kg^{-1}$			$g.pot^{-1}$	%
42	13.3	128	2.08	1.39	0.66	24.7	13.9	5.47
48	9.3	114	0.89	1.56	bd	24.1	13.2	5.65
52	10.6	103	1.54	1.57	4.70 x)	23.0	11.0	5.55
58	13.7	117	1.31	1.31	1.53	23.4	13.0	5.58
63	10.9	122	0.75	1.58	0.68	23.8	12.2	5.45
66	10.3	121	1.24	1.32	0.66	25.4	11.4	5.44
73	10.1	125	1.07	1.55	0.88	25.0	11.6	5.57
79	10.0	123	0.61	0.67 x)	0.44	24.3	11.3	5.75
$\bar{x}$	11.0	119	1.19	1.47	0.80	24.2	12.2	5.56
s	1.6	8	0.47	0.12	0.39	0.8	1.1	0.11

bd = below detection limit of 0.10 $mg.kg^{-1}$.

x). excluded from calculation of mean values.

Appendix D

Heavy-metal concentration and yield of radish tuber 1).

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni $mg.kg^{-1}$	Pb	Cd	average yield $g.pot^{-1}$	dry matter %
44-47	3.7	27	1.34	0.35	bd	0.13	8.60	5.87
51-60	4.8	33	2.25	0.47	0.21	0.22	4.42	6.69
62-69	3.4	30	1.46	0.27	bd	0.15	8.60	5.68
74-77	3.8	30	1.37	0.27	bd	0.19	5.42	7.22
$\bar{x}$	3.9	30	1.61	0.34	0.21	0.17	6.76	6.37
s	0.6	2	0.43	0.09		0.04	2.16	0.72

Sediment: Spieringpolder, code SP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	average yield	dry matter
43-46	5.7	60	2.10	0.48	0.77	0.72	5.18	5.35
54-56	7.4	69	3.64	0.88	2.54	0.75	3.40	5.03
61-68	7.4	75	4.55	0.99	4.63	0.83	4.88	5.47
71-78	10.0	89	6.61	1.56	6.05	0.96	3.17	5.68
$\bar{x}$	7.6	73	4.23	0.98	3.50	0.82	4.16	5.38
s	1.8	12	1.88	0.45	2.32	0.11	1.02	0.27

Sediment: Oostabtspolder, code OP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	average yield	dry matter
45-49	7.6	93	3.16	1.11	1.91	1.81	3.16	6.00
55-57	5.7	82	1.68	0.70	0.78	1.55	2.82	6.18
64-70	7.7	93	4.25	1.08	2.33	1.97	4.71	5.46
72-80	9.7	98	6.44	1.41	5.09	2.19	3.36	5.78
$\bar{x}$	7.7	92	3.88	1.08	2.53	1.88	3.51	5.86
s	1.6	7	2.00	0.29	1.83	0.27	0.83	0.31

Sediment: Broekpolder, code BP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	average yield	dry matter
41-50	8.1	124	1.78	1.06	1.91	2.86	2.86	5.55
53-59	12.4	139	6.78	1.77	5.08	3.04	2.78	5.44
65-67	14.8	150	9.54	2.11	6.23	3.46	2.44	5.71
75-76	12.8	137	7.97	1.80	5.50	3.08	2.95	5.14
$\bar{x}$	12.0	138	6.52	1.69	4.68	3.11	2.76	5.46
s	2.8	11	3.35	0.44	1.91	0.25	0.22	0.24

Sediment: Neckar sludge, code NS

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	average yield	dry matter
42-48	13.4	124	3.49	3.48	3.26	10.4	3.83	5.43
52-58	15.8	123	5.17	3.55	3.33	10.5	3.13	5.40
63-66	19.4	126	9.02	4.34	5.65	10.7	3.63	5.35
73-79	18.3	123	8.92	4.43	5.54	10.4	3.48	5.30
$\bar{x}$	16.7	124	6.65	3.95	4.45	10.5	3.52	5.37
s	2.7	1	2.77	0.50	1.33	0.1	0.30	0.06

bd = below detection limit of 0.10 $mg.kg^{-1}$.

1) = radish tubers from 2 pots have been combined and analyzed as one sample.

Appendix E

Heavy-metal concentration and yield radish leaves.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
44	3.2	33	bd	0.23	0.70	0.57	13.2	7.53
47	4.8	139	1.19	0.22	11.7 x)	0.76	13.2	7.55
51	5.4	60	1.57	0.44	1.10	0.64	11.7	7.89
60	3.1	28	1.14	0.22	0.33	0.66	9.0	8.04
62	5.3	107	1.19	0.22	0.54	0.51	14.2	7.62
69	4.6	87	1.52	0.22	0.43	0.65	10.1	7.78
74	7.0	46	0.99	0.45	0.45	0.75	11.4	7.77
77	4.7	101	0.83	0.28	0.52	0.71	11.9	7.55
$\bar{x}$	4.8	75	1.20	0.29	0.58	0.66	11.8	7.72
s	1.3	40	0.27	0.10	0.26	0.09	1.7	0.19

Sediment: Spieringpolder, code SP

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
43	5.1	82	0.45	0.22	1.01	2.51	10.2	6.21
46	4.2	132	0.61	0.44	1.09	2.01	11.7	5.97
54	7.2	98	1.60	0.34	2.02	2.59	9.6	6.08
56	5.9	92	1.56	0.34	1.35	2.18	10.7	5.96
61	7.2	93	0.76	0.45	1.58	2.24	11.0	6.19
68	9.0	60	2.23	0.31	1.23	2.41	11.4	6.13
71	7.3	101	2.00	0.89 x)	1.44	2.47	11.2	5.80
78	13.1 x)	214 x)	1.56	0.22	1.11	2.31	10.4	6.09
$\bar{x}$	6.6	94	1.35	0.33	1.35	2.34	10.8	6.05
s	1.6	22	0.66	0.09	0.33	0.19	0.7	0.14

Sediment: Oostabtspolder, code OP

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
45	3.5	85	0.53	0.66	1.10	3.35	10.5	6.46
49	6.5	120	1.02	0.54	0.65	3.97	9.3	7.32
55	5.7	115	1.29	0.22	0.56	3.70	7.6	6.81
57	4.6	103	1.78	0.56	0.89	3.42	9.8	6.32
64	6.7	96	0.99	0.33	1.87	4.40	11.9	6.25
70	6.6	126	1.85	0.43	1.29	3.98	11.7	6.33
72	6.7	96	1.29	0.45	1.12	2.90	8.3	6.43
80	4.7	99	1.40	0.47	1.11	3.65	12.5	6.45
$\bar{x}$	5.6	105	1.27	0.46	1.07	3.67	10.2	6.55
	1.2	14	0.43	0.14	0.41	0.46	1.8	0.36

Sediment: Broekpolder, code BP

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
41	8.7	186	1.06	1.11	1.99	6.31	9.0	6.69
50	10.[illegible]	190	1.67	1.33	6.31 x)	6.49	10.7	6.29
53	9.8	207	1.94	0.66	1.33	6.29	10.1	6.33
59	6.1	164	1.40	0.90	1.35	6.37	9.1	6.65
65	9.3	162	1.33	0.88	1.76	6.95	9.9	6.22
67	8.0	117	1.48	1.32	2.19	6.76	10.3	6.39
75	10.6	231	2.30	0.85	2.23	6.56	10.2	6.13
76	9.8	221	1.70	0.66	1.98	6.02	10.5	6.24
$\bar{x}$	9.0	185	1.61	0.96	1.83	6.47	10.0	6.37
s	1.4	37	0.39	0.26	0.37	0.29	0.6	0.20

Sediment: Neckar sludge, code NS

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
42	13.5	189	1.21	2.20	4.84 x)	35.3	10.2	6.56
48	15.5	201	1.72	2.23	0.67	32.4	9.9	6.39
52	13.1	214	1.32	2.01	0.78	31.6	10.0	6.74
58	11.4	214	1.65	1.98	1.10	36.4	9.1	6.64
63	15.2	186	1.39	2.25	1.35	33.1	9.9	6.58
66	11.2	147	1.29	2.12	1.48	33.7	10.5	6.23
73	12.0	132	1.60	1.99	1.54	32.3	11.6	6.39
79	5.2 x)	90	1.50	2.11	1.56	33.7	10.1	6.14
$\bar{x}$	13.1	172	1.46	2.11	1.21	33.6	10.2	6.46
s	1.7	44	0.19	0.11	0.37	1.6	0.7	0.21

x) - excluded from calculation of mean values
bd = concentration below detection limit of 0.25 mg.kg^{-1}.

Appendix F

Heavy-metal concentration and yield of spring wheat grain.

Pot no.	Cu	Zn	Cr	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
Sediment: Noordbovenpolder, code NP								
5	8.2	54	bd	0.05	0.05	0.11	50.7	89.1
7	8.8	60	bd	0.11	0.05	0.12	51.0	89.2
12	7.9	60	bd	0.11	0.16	0.11	49.7	88.9
20	7.4	50	bd	0.05	bd	0.12	58.7	98.5
$\bar{x}$	8.1	56	bd	0.08	0.09	0.12	52.5	91.4
s	0.6	5		0.03	0.06	0.01	4.2	4.7
Sediment: Spieringpolder, code SP								
3	7.2	65	bd	0.19	0.05	0.26	51.4	89.1
8	7.7	69	bd	0.21	0.05	0.26	52.5	88.7
15	6.9	70	bd	0.11	0.16	0.24	50.9	89.0
18	7.1	70	bd	0.11	0.16	0.28	50.5	89.1
$\bar{x}$	7.2	68	bd	0.16	0.11	0.26	51.3	89.0
s	0.3	3		0.05	0.06	0.02	0.9	0.2
Sediment: Oostabtspolder, code OP								
4	6.9	82	bd	0.32	0.16	0.56	39.7	89.0
9	8.0	93	bd	0.32	0.05	0.63	45.8	88.2
11	7.8	91	0.46	0.36	0.36	0.66	50.1	89.0
16	7.1	87	bd	0.31	0.10	0.60	41.1	88.8
$\bar{x}$	7.4	88	bd	0.33	0.17	0.61	44.2	88.8
s	0.5	5		0.02	0.14	0.04	4.7	0.4
Sediment: Broekpolder, code BP								
1	10.2	107	bd	0.48	0.11	0.70	42.2	89.2
6	10.6	112	bd	0.43	0.11	0.67	38.0	89.2
14	9.2	105	bd	0.45	0.08	0.56	37.0	88.7
19	9.7	117	bd	0.54	0.05	0.79	39.4	88.9
$\bar{x}$	9.9	110	bd	0.48	0.09	0.68	39.2	89.0
s	0.6	5		0.05	0.03	0.09	2.3	0.2
Sediment: Neckar sludge, code NS								
2	10.9	101	bd	0.68	0.16	2.44	47.6	89.0
10	10.1	90	bd	0.75	0.05	2.15	54.3	88.9
13	10.3	98	bd	0.68	0.16	2.13	49.0	89.3
17	10.1	102	bd	0.76	0.27	2.42	45.8	88.9
$\bar{x}$	10.4	98	bd	0.72	0.16	2.29	49.2	89.0
s	0.4	6		0.04	0.09	0.17	3.7	0.2

bd : below detection limit (Cr 0.25 $mg.kg^{-1}$, Pb 0.10 $mg.kg^{-1}$).

Appendix G

Heavy-metal concentration and yield of spring wheat straw.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
5	3.8	22	bd	0.21	1.18	0.23	54.7	91.2
7	3.4	21	bd	0.22	1.09	0.20	50.4	87.2
12	3.6	28	bd	0.17	1.38	0.30	48.7	87.3
20	3.7	18	bd	0.11	0.98	0.23	52.5	80.2
$\bar{x}$	3.6	22	bd	0.18	1.16	0.24	51.6	86.5
s	0.2	4		0.05	0.17	0.04	2.6	4.6

Sediment: Spieringpolder, code SP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
3	3.2	72	bd	0.32	1.37	0.52	56.1	92.4
8	3.0	76	0.54	0.22	1.19	0.54	53.0	87.2
15	3.8	76	bd	0.33	1.55	0.61	50.0	88.2
18	3.5	67	bd	0.32	1.37	0.57	49.7	88.1
$\bar{x}$	3.4	73	bd	0.30	1.37	0.56	52.2	89.0
s	0.4	4		0.05	0.15	0.04	3.0	2.3

Sediment: Oostabtspolder, code OP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
4	4.4	98	bd	0.43	1.70	1.25	45.9	90.4
9	3.7	101	bd	0.22	1.29	1.12	47.9	87.4
11	3.6	103	bd	0.32	1.38	1.27	48.2	87.2
16	4.1	96	bd	0.33	1.75	1.07	49.6	88.1
$\bar{x}$	3.9	99	bd	0.33	1.53	1.18	47.9	88.3
s	0.4	3		0.09	0.23	0.10	1.5	1.5

Sediment: Broekpolder, code BP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
1	4.8	159	0.50	0.87	1.73	1.45	52.9	91.7
6	4.9	183	0.27	0.43	1.73	1.54	47.8	86.9
14	4.9	164	0.29	0.33	1.87	1.32	46.4	87.5
19	4.7	165	bd	0.23	1.44	1.45	42.6	87.5
$\bar{x}$	4.8	168	0.35	0.46	1.69	1.44	47.2	88.4
s	0.1	11	0.13	0.28	0.18	0.09	4.3	2.2

Sediment: Neckar sludge, code NS

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
2	6.2	98	bd	2.58 x)	1.72	5.46	51.3	91.4
10	5.9	95	bd	0.33	1.42	5.32	50.6	87.4
13	6.8	99	0.29	0.33	1.66	5.47	46.7	87.8
17	6.8	94	0.50	0.33	1.43	5.81	45.1	87.9
$\bar{x}$	6.4	97		0.33	1.56	5.52	48.4	88.6
s	0.5	3		0.0	0.16	0.21	3.0	1.9

x) = excluded from calculation of mean values.
bd = below detection limit of 0.25 $mg.kg^{-1}$.

Appendix H

Heavy-metal concentration and yield of grass, first cut.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
21	15.0	45	bd	1.78	1.94x)	0.48	6.09	16.6
29	16.0	44	bd	1.96	0.23	0.49	5.26	15.8
35	16.6	45	bd	2.19	0.44	0.38	6.44	16.7
37	16.3	40	bd	1.98	0.33	0.36	5.78	17.5
$\bar{x}$	16.0	43	bd	1.98	0.33	0.43	5.89	16.7
s	0.7	2		0.17	0.11	0.07	0.50	0.7

Sediment: Spieringpolder, code SP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
25	19.5	40	bd	0.80	0.51	0.70	7.91	14.7
28	18.6	42	bd	0.83	0.39	0.73	7.28	15.3
33	17.4	41	bd	0.88	0.44	0.67	7.71	15.8
40	17.5	40	bd	0.96	0.63	0.71	7.31	15.3
$\bar{x}$	18.3	41	bd	0.87	0.49	0.70	7.55	15.3
s	1.0	1		0.07	0.10	0.03	0.31	0.5

Sediment: Oostabtspolder, code OP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
22	19.8	44	bd	2.41	1.34	1.15	6.18	14.6
30	17.7	46	bd	1.55	2.55x)	1.24	5.27	13.7
34	18.8	48	bd	1.73	1.08	1.23	6.16	13.8
36	18.7	47	bd	1.60	0.88	1.09	6.36	13.8
$\bar{x}$	18.8	46	bd	1.82	1.10	1.18	5.99	14.0
s	0.9	2		0.40	0.23	0.07	0.49	0.4

Sediment: Broekpolder, code BP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
23	19	44	1.47	2.63	0.66	1.14	3.78	14.3
27	19	45	0.34	1.87	0.50	1.21	3.93	14.1
31	20	45	bd	2.19	8.90x)	1.16	4.41	15.9
38	19	43	bd	2.41	0.76	0.99	4.56	14.6
$\bar{x}$	19	44	bd	2.28	0.64	1.13	4.17	14.7
s	1	1		0.32	0.13	0.09	0.37	0.8

Sediment: Neckar sludge, code NS

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
24	18	56	0.97	5.46	0.44	3.86	9.20	14.4
26	22	59	0.33	4.99	0.43	3.77	7.41	14.1
32	20	62	0.29	5.48	0.66	3.74	6.34	14.8
39	19	54	bd	5.48	0.55	3.65	8.39	14.5
$\bar{x}$	20	58	0.53	5.35	0.52	3.76	7.83	14.5
s	2	4	0.38	0.24	0.11	0.09	1.24	0.3

x) = excluded from calculation of mean values.

bd = below detection limit of 0.25 $mg.kg^{-1}$.

Appendix I

Heavy-metal concentration and yield of grass, second cut.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni $mg.kg^{-1}$	Pb	Cd	yield $g.pot^{-1}$	dry matter %
21	16.4	31	0.68	1.20	0.34	0.29	4.01	16.8
29	16.1	36	1.25	1.53	0.64	0.22	4.39	17.2
35	16.0	34	0.67	1.55	0.48	0.36	5.13	16.5
37	21.4	33	0.72	1.21	1.06	0.32	3.83	16.8
$\bar{x}$	17.5	34	0.83	1.37	0.63	0.30	4.34	16.8
s	2.6	2	0.28	0.19	0.31	0.06	0.58	0.3

Sediment: Spieringpolder, code SP

25	15.4	29	1.42	0.55	0.44	0.47	5.15	16.5
28	16.9	27	0.26	0.71	0.44	0.40	7.36	17.4
33	18.1	27	0.52	0.56	0.56	0.53	7.01	16.3
40	15.5	27	1.15	1.00	0.78	0.52	5.98	16.8
$\bar{x}$	16.5	27	0.84	0.71	0.56	0.48	6.37	16.8
s	1.3	1	0.54	0.21	0.16	0.06	1.01	0.5

Sediment: Oostabtspolder, code OP

22	15.9	25	0.79	0.61	0.46	1.18	3.80	15.8
30	16.0	31	0.31	0.87	0.65	1.09	5.47	15.0
34	18.2	30	0.82	0.85	0.53	1.26	7.48	15.0
36	22.2	33	0.84	1.18	0.75	1.19	10.45	14.7
$\bar{x}$	18.1	30	0.69	0.88	0.60	1.18	6.80	15.1
s	2.9	3	0.25	0.23	0.13	0.07	2.86	0.5

Sediment: Broekpolder, code BP

23	17.1	32	0.83	1.21	0.61	1.09	3.16	14.2
27	20.9	35	0.26	1.63	1.31	1.12	5.19	14.8
31	23.3	37	0.52	1.58	0.79	1.25	4.15	14.0
38	21.0	32	0.87	1.46	1.06	1.21	4.64	14.6
$\bar{x}$	20.6	34	0.62	1.47	0.94	1.17	4.28	14.4
s	2.6	2	0.29	0.19	0.31	0.08	0.86	0.4

Sediment: Neckar sludge, code NS

24	15.8	38	0.49	3.38	0.76	3.19	9.52	15.8
26	16.6	38	0.88	3.44	0.33	2.89	9.47	15.9
32	21.3	38	0.57	4.16	0.55	3.48	9.63	15.6
39	18.7	35	0.56	3.40	0.66	3.77	9.24	15.9
$\bar{x}$	18.1	37	0.63	3.60	0.58	3.33	9.46	15.8
s	2.5	2	0.17	0.38	0.18	0.38	0.16	0.1

Appendix J

Heavy-metal concentration and yield of grass, third cut.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni mg.kg^{-1}	Pb	Cd	yield g.pot^{-1}	dry matter %
21	11.6	34	0.82	2.20	17.1	0.28	7.07	18.3
29	12.9	34	1.06	1.48	5.40	0.30	5.69	16.6
35	12.1	36	0.45	1.35	6.65	0.28	5.18	18.7
37	11.7	39	0.57	1.33	2.88	0.27	6.71	18.0
$\bar{x}$	12.1	36	0.73	1.59	8.01	0.28	6.16	17.9
s	0.6	3	0.27	0.41	6.26	0.01	0.88	0.9

Sediment: Spieringpolder, code SP

25	13.2	33	0.25	0.67	2.77	0.42	6.23	17.3
28	12.1	28	0.51	0.76	3.27	0.42	7.01	17.1
33	12.1	32	bd	0.67	7.10	0.49	5.21	20.4
40	11.6	29	0.48	0.50	2.13	0.48	4.50	19.9
$\bar{x}$	12.3	30	0.41	0.65	3.82	0.45	5.74	18.7
s	0.7	2	0.14	0.11	2.24	0.04	1.11	1.7

Sediment: Oostabtspolder, code OP

22	12.3	33	1.25	1.16	9.38	1.18	5.38	16.7
30	12.8	31	0.52	0.84	4.30	1.12	8.63	17.3
34	12.1	33	0.26	0.95	4.14	1.11	10.17	18.7
36	11.7	39	0.25	1.11	3.13	1.03	11.50	18.6
$\bar{x}$	12.2	34	0.57	1.02	5.24	1.11	8.92	17.8
s	0.5	4	0.47	0.15	2.81	0.06	2.64	1.0

Sediment: Broekpolder, code BP

23	13.1	35	1.04	1.32	7.39	1.19	3.26	15.6
27	13.0	34	0.59	1.49	5.66	1.16	7.31	15.6
31	12.9	34	0.53	1.28	2.20	1.14	3.06	15.8
38	13.7	34	1.35	1.30	8.06	1.17	4.29	17.5
$\bar{x}$	13.2	34	0.88	1.35	5.83	1.17	4.48	16.1
s	0.4	1	0.39	0.10	2.62	0.02	1.96	0.9

Sediment: Neckar sludge, code NS

24	12.6	38	0.30	3.25	4.68	2.88	9.36	16.4
26	13.8	41	1.17	3.42	6.31	2.81	10.17	17.2
32	13.9	39	0.57	3.40	3.54	3.12	8.17	17.4
39	13.3	40	0.59	3.10	3.05	3.23	10.28	17.5
$\bar{x}$	13.4	40	0.66	3.29	4.40	3.01	9.49	17.1
s	0.6	1	0.37	0.15	1.45	0.20	0.97	0.5

bd = below detection limit of 0.25 mg.kg^{-1}.

Appendix K

Heavy-metal concentration and yield of grass, fourth cut.

Sediment: Noordbovenpolder, code NP

Pot no.	Cu	Zn	Cr	Ni	Pb	Cd	yield	dry matter
				$mg.kg^{-1}$			$g.pot^{-1}$	%
21	10.1	34	0.96	1.30	1.30	0.28	5.68	19.7
29	11.3	33	0.83	1.31	0.87	0.34	2.51	16.2
35	11.2	33	1.10	1.20	0.54	0.25	4.30	19.3
37	11.1	30	0.73	1.41	1.21	0.24	6.82	18.4
$\bar{x}$	10.9	33	0.91	1.31	0.98	0.28	4.83	18.4
s	0.6	2	0.16	0.09	0.35	0.05	1.86	1.6
Sediment: Spieringpolder, code SP								
25	11.5	32	0.50	0.40	1.61	0.50	4.85	19.9
28	11.7	35	1.03	0.69	0.96	0.49	6.24	19.7
33	12.4	35	0.78	0.65	0.87	0.53	5.25	20.3
40	11.7	34	0.75	0.55	0.79	0.61	6.10	21.9
$\bar{x}$	11.8	34	0.77	0.57	1.06	0.53	5.61	20.5
s	0.4	2	0.22	0.13	0.37	0.05	0.67	1.0
Sediment: Oostabtspolder, code OP								
22	9.5	25	bd	0.56	1.35	1.11	6.24	19.2
30	11.4	31	bd	0.85	0.75	1.10	8.27	17.9
34	11.5	33	0.73	0.83	0.73	1.15	8.35	19.1
36	10.1	28	0.51	0.62	1.04	0.97	9.78	18.7
$\bar{x}$	10.6	29		0.72	0.97	1.08	8.16	18.7
s	1.0	3		0.15	0.29	0.08	1.46	0.6
Sediment: Broekpolder, code BP								
23	12.9	34	bd	1.34	6.67	1.19	3.99	18.3
27	12.8	36	1.06	1.36	1.04	1.10	6.72	16.9
31	13.2	45	0.55	1.48	0.80	1.32	4.23	19.2
38	12.5	35	0.74	1.49	1.98	1.34	3.31	16.7
$\bar{x}$	12.9	37	0.78	1.42	2.62	1.24	4.56	17.8
s	0.3	5	0.26	0.08	2.75	0.11	1.49	1.2
Sediment: Neckar sludge, code NS								
24	11.9	37	1.45	2.57	1.10	2.94	6.92	19.1
26	12.5	37	0.50	2.90	0.88	2.95	6.51	19.4
32	13.1	46	0.46	2.91	0.67	3.74	6.47	19.9
39	12.7	41	0.37	3.13	0.53	3.78	9.57	19.8
$\bar{x}$	12.6	40	0.70	2.88	0.80	3.38	7.37	19.6
s	0.5	4	0.51	0.23	0.25	0.50	1.48	0.4

bd : below detection limit of 0.25 $mg.kg^{-1}$.

Appendix L

Linear correlation coefficients (r^2) for total and DTPA-extractable heavy metals from sediments versus plant heavy-metal concentrations of *Cyperus esculentus* and some agronomic plant species.

Heavy metal	Cyperus esculentus				Lettuce		Radish				Spring wheat				Red fescue grass leaves							
	flooded		upland				tuber		leaf		grain		straw		1^{st} cut		2^{nd} cut		3^{rd} cut		4^{th} cut	
	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA
Cu	0.23	0.78	0.07	0.06	0.57	0.49	0.91	0.92	0.74	0.77	0.75	0.77	0.86	0.91	0.74	0.70	0.28	0.21	0.71	0.71	0.67	0.64
Zn	0.36	0.13	0.63	0.74	0.69	0.88	0.78	0.93	0.54	0.66	0.72	0.92	0.88	0.99	-0.09	0.16	-0.17	0.13	-0.30	<0.01	0.24	0.33
Ni	0.62	0.62	-0.39	-0.23	0.89	0.89	$\underline{0.95}$	0.93	$\underline{0.95}$	0.92	$\underline{0.97}$	$\underline{0.95}$	0.48	0.46	0.88	0.91	0.85	0.86	0.79	0.83	0.83	0.83
Pb	0.17	0.47	0.29	0.44	0.04	0.30	0.68	0.44	0.04	-0.10	0.03	0.13	0.62	0.14	0.25	-0.20	0.30	-0.24	-0.29	-0.39	0.34	-0.13
Cd	0.84	0.91	$\underline{0.97}$	$\underline{0.97}$	$\underline{0.97}$	$\underline{0.98}$	$\underline{0.97}$	$\underline{0.99}$	0.94	$\underline{0.97}$	$\underline{0.96}$	$\underline{0.98}$	$\underline{0.96}$	$\underline{0.98}$	$\underline{0.95}$	$\underline{0.98}$	$\underline{0.96}$	$\underline{0.98}$	$\underline{0.98}$	$\underline{0.99}$	$\underline{0.96}$	$\underline{0.98}$

Underlined correlation coefficients are significant at P = 0.05

Appendix M

Linear correlation coefficients (r^2) for total and DTPA-extractable heavy metals from sediments versus total uptake (concentration x yield) of heavy metals by Cyperus esculentus and some agronomic plant species.

Heavy metal	Cyperus esculentus				Lettuce		Radish				Spring wheat				Red fescue grass leaves							
	flooded		upland				tuber		leaf		grain		straw		1^{st} cut		2^{nd} cut		3^{rd} cut		4^{th} cut	
	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA	total	DTPA
Cu	<0.01	0.08	0.06	0.04	0.28	0.27	0.53	0.66	0.44	0.49	0.17	0.29	0.68	0.79	0.11	0.20	0.26	0.32	0.13	0.20	0.19	0.22
Zn	<0.01	0.03	0.26	0.41	0.02	0.38	0.29	0.45	0.21	0.01	0.29	0.51	0.80	$\underline{0.97}$	0.04	0.03	<0.01	0.01	0.07	0.01	<0.01	0.02
Ni	0.15	0.08	0.01	0.03	0.81	0.82	0.83	0.82	0.88	0.83	$\underline{0.95}$	0.93	0.21	0.20	0.70	0.77	0.75	0.78	0.63	0.73	0.67	0.72
Pb	0.18	0.11	0.20	0.01	0.01	0.04	0.32	0.31	<0.01	0.02	<0.01	0.02	0.36	0.05	0.06	0.03	0.06	0.01	0.13	0.09	0.12	0.01
Cd	0.77	0.81	0.85	0.77	0.97	$\underline{0.97}$	0.90	$\underline{0.95}$	0.88	0.93	0.89	$\underline{0.95}$	0.91	$\underline{0.96}$	0.78	0.85	0.83	0.89	0.82	0.88	0.76	0.81

Underlined correlation coefficients are significant at P = 0.05

Appendix N

Linear correlation coefficients (r^2) for *Cyperus* heavy-metal concentrations versus crop metal concentrations (conc.), and for *Cyperus* heavy-metal uptake per pot versus crop heavy-metal uptake per pot (upt.).

Heavy metal	Lettuce		Radish				Spring wheat				Red fescue grass leaves							
			tuber		leaf		grain		straw		1st cut		2nd cut		3rd cut		4th cut	
	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.	conc.	upt.
Cu	0.05	0.04	0.13	0.19	0.08	0.31	0.85	0.55	0.66	0.64	0.01	0.64	0.62	0.67	0.44	0.68	0.20	0.66
Zn	0.65	0.65	0.80	0.39	0.51	0.89	0.85	0.44	0.78	0.61	0.44	0.88	<0.01	0.34	0.01	0.37	<0.01	0.17
Ni	<0.01	0.03	0.31	0.14	0.05	0.05	0.09	0.01	0.26	0.01	0,44	0.27	0.53	0.20	0.87	0.18	0.52	0.49
Pb	0.72	0.03	0.38	0.21	0.18	0.55	0.23	0.66	0.10	0.26	<0.01	0.81	0.13	0.03	0.97	0.38	0.03	0.35
Cd	0.91	0.90	0.76	0.71	0.95	0.87	0.96	0.47	0.98	0.68	0.86	0.01	0.90	0.11	0.94	0.06	0.97	0.13

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